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APPLICATION

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TITLE: WAVEGUIDE MODE STRIPPER FOR INTEGRATED OPTICAL COMPONENTS

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WAVEGUIDE MODE STRIPPER FOR INTEGRATED OPTICAL COMPONENTS

FIELD OF THE INVENTION

The present invention relates to integrated optical components and, more specifically, to a waveguide mode stripper for integrated optical components.

BACKGROUND

As telecommunications and data communications increasingly adopt optical fiber as a preferred communication medium, integrated electrical components, generally present in communications equipment, are being replaced by equivalent integrated optical components, including waveguides, optical amplifiers, splitters, etc.

To pass from optical fiber to integrated optical components, an optical signal is first received by a waveguide, often formed in the same medium on which the integrated optical components have been formed. The optical signal carried by a waveguide can be said to have at least one "mode", where a mode is one of number of possible patterns of propagating or evanescent electromagnetic fields that maintain their transverse field distribution during propagation. Each mode is characterized by frequency, polarization, electric field strength and magnetic field strength. The electromagnetic field pattern of a mode depends on the frequency of the signal and refractive indices, dielectric constants and geometry of the waveguide.

Multimode Interference (MMI) devices rely on a self-imaging property of multimode waveguides. Self-imaging is the property by which an input field pattern is reproduced in single or multiple images at periodic intervals along the propagation direction of the waveguide. This self-imaging is a result of the (near quadratic) dependence of a propagation constant with the mode number.

An MMI coupler is an exemplary MMI device that consists of input waveguides and output waveguides separated by an MMI region. The MMI region supports a large number of modes that propagate with different phase velocities leading to periodic self-imaging. There may be multiple inputs to the MMI region and multiple outputs. The dimensions of the MMI region are selected based on the wavelength of the signal of interest and establish the nature of the optical signal on

the outputs as a function of the signals on the inputs. For instance, an appropriately dimensioned MMI coupler may have a single input and divide the signal in that input such that the signal is split between two outputs.

MMI devices have become important components within the integrated optical circuits that require N×M power splitting structures, which distribute (not necessarily uniformly) the power of N inputs to M outputs. Exemplary integrated optical circuits that require power splitting structures include ring lasers, arrayed waveguide gratings, interferometric modulators and optical switches. A Mach-Zehnder modulator is another example of an integrated optical circuit that requires a splitting structure. The configuration of a power splitting structure in an interferometric modulator determines a power splitting ratio, where the power splitting ratio indicates a division of input power between a number of output powers, for instance, two output powers.

Like integrated electrical components, integrated optical components need to be coupled. However, unlike electrical components wherein electrical connections merely need to contact, when a fiber is coupled to a waveguide leading to integrated optical components, misalignments may occur. Misaligned optical coupling can excite modes other than the fundamental mode in the input waveguide of a power splitting structure, which can lead to variations in the power splitting ratio of the power splitting structure. Fixing this power splitting ratio is critical to the performance of interferometric modulators.

If the coupling between a fiber and a waveguide can be accomplished with sub-micron precision, the splitting ratio may be fixed, but such requirements lead to very small manufacturing tolerances.

While there are a few waveguides and splitter designs that allow fixed split ratios regardless of misalignment, if device requirements do not accommodate these designs, there is no known solution to the problem of the dependence of splitting ratios on misalignment.

An undesired power splitting ratio can degrade the device performance of a Mach-Zehnder or other interferometric modulator.

Where misalignments at the input to an integrated optical device are one problem, another problem arises at the output coupling between a waveguide and a fiber. Often a portion of the optical signal on the output waveguide of the optical component in question is reflected back at the optical component by the coupling between the output waveguide and the fiber. These reflections are generally called "backreflections".

Commonly, these backreflections may be reduced by coating the facet of the output waveguide with an appropriate material. Although backreflections may be reduced by this method, the reduction may not be sufficient for some applications. Further, the accuracy with which the thickness of the coating must be applied requires very small tolerances to be observed and, even then, the effectiveness of the coating in reducing backreflections is very sensitive to variations in the wavelength of the signal to be reduced.

Another method of reducing backreflections involves angling the waveguide facets. However, this method may still not reduce backreflectivity enough for some applications, especially those applications that require waveguides with small fundamental mode field diameters or large refractive index step waveguides. Furthermore, angling waveguides leads to packaging complexity.

Clearly, there is a need to reduce the negative effect of the higher order modes present in a waveguide after a misaligned coupling. Further, it would be advantageous to find an alternative to current methods used to reduce backreflections.

SUMMARY

By stripping higher order modes from a signal input to a splitting structure, a mode stripper can significantly reduce variations in the power splitting ratio caused by misaligned optical couplings at the input to integrated optical components. The mode stripper can thus increase the packaging tolerances and performance of these integrated optical components. The mode stripper can also be used at the output of integrated optical components to reduce backreflections.

In accordance with an aspect of the present invention there is provided an integrated optical circuit including an input waveguide, an imaging multimode interference device adapted to substantially remove all modes but a fundamental mode of an optical signal received from the input waveguide and an optical power splitter structure in optical communication with the imaging multimode interference device.

In accordance with another aspect of the present invention there is provided a method for suppressing propagating lateral waveguide field oscillations at the input of an optical power splitter structure including fabricating an imaging multimode interference device in optical communication with the optical power splitter structure.

In accordance with a further aspect of the present invention there is provided an integrated optical circuit including an imaging multimode interference device in optical communication with an optical power splitting structure.

In accordance with an even further aspect of the present invention there is provided an integrated optical circuit including a semiconductor optical amplifier having an angled output and an imaging multimode interference device between the semiconductor optical amplifier and the angled output.

In accordance with a still further aspect of the present invention there is provided an integrated optical circuit including a waveguide device having an angled output and an imaging multimode interference device between the waveguide device and the angled output.

In accordance with an even further aspect of the present invention there is provided for use of an imaging multimode interference device as an optical mode stripper in an integrated optical circuit.

In accordance with a still further aspect of the present invention there is provided for use of an imaging multimode interference device to substantially remove all modes but a fundamental mode of an optical signal received at an input to the multimode interference device.

In accordance with an even further aspect of the present invention there is provided a semiconductor optical amplifier including an imaging multimode interference device adapted to substantially remove all modes but a fundamental mode of an optical signal received from an input waveguide and an electrode in contact with the multimode interference device adapted to change the optical properties of the multimode interference device through application of an electrical signal.

In accordance with a still further aspect of the present invention there is provided an optical attenuator including an input waveguide, an imaging multimode interference device adapted to substantially remove all modes but a fundamental mode of an optical signal received from the input waveguide and an electrode adapted to apply a bias voltage to a surface of the imaging multimode interference device.

Other aspects and features of the present invention will become apparent to those of ordinary skill in the art upon review of the following description of specific embodiments of the invention in conjunction with the accompanying figures.

BRIEF DESCRIPTION OF THE DRAWINGS

In the figures which illustrate example embodiments of this invention:

FIG. **1A** illustrates a perspective view of a multimode interference device for use as a mode stripper according to an embodiment of the present invention;

FIG. **1B** illustrates a top view of the mode stripper of FIG. **1** showing a basic structure for an MMI region;

FIG. **1C** illustrates a top view of a first alternate structure for the MMI region of the mode stripper of FIG. **1**;

FIG. **1D** illustrates a top view of a second alternate structure for the MMI region of the mode stripper of FIG. **1**;

FIG. **2A** illustrates a mode stripper in use according to a first embodiment of the present invention;

FIG. **2B** illustrates a mode stripper in use according to a second embodiment of the present invention;

FIG. **3** illustrates a first exemplary integrated optical circuit wherein a mode stripper is provided on each side of a semiconductor optical amplifier according to an embodiment of the present invention;

FIG. **4** illustrates a second exemplary integrated optical circuit wherein a mode stripper is provided on each side of an optical waveguide device according to an embodiment of the present invention;

FIG. **5** illustrates a semiconductor optical amplifier combined with a mode stripper according to an embodiment of the present invention;

FIG. **6** illustrates an alternative configuration of a mode stripper according to an embodiment of the present invention;

FIG. **7** illustrates an optical integrated circuit including a mode stripper and a interferometric modulator according to an embodiment of the present invention; and

FIG. **8** illustrates the impact of an embodiment of the present invention on a the Split Ratio of a Butterfly MMI.

DETAILED DESCRIPTION

FIG. **1A** illustrates, in perspective, a strongly guided 1-to-1 imaging MMI device **100** for use as a mode stripper. It is noted that "1-to-1" means the device has one input and one output. To form the mode stripper **100**, a structure is grown epitaxially and includes upper cladding layers **102**, a core layer **104** and under cladding layers **106**. The epitaxial structure is then etched, using a conventional photolithography process, to form an input waveguide **108**, a multimode interference (MMI) region **112** and an output waveguide **110**. A top view of the mode stripper **100** is presented in FIG. **1B**.

Additional shapes may be used for the MMI region **112**, as illustrated as top views in FIGS. **1C** and **1D**. A first alternative mode stripper **100C**, in FIG. **1C**, has an MMI region **112C** whose side structures are angled outwardly, while a second alternative mode stripper **100D**, in FIG. **1D**, has an MMI region **112D** whose side structures are angled inwardly. The angled side structures of the MMI region **112C** of FIG. **1C** and the MMI region **112D** of FIG. **1D** may be used to reduce optical backreflections emanating from the mode stripper. As will be apparent to a person skilled in the art, combinations of the structures shown in FIGS. **1B**, **1C** and **1D** are also possible.

As will be apparent to a person skilled in the art, the addition of an electrode to any of the MMI implementations illustrated in FIGS. **1B**, **1C** and **1D** in combination with an appropriate epitaxial structure allows the resultant mode stripper to be used as an optical attenuator. Furthermore, the large area of the resultant device provides excellent thermal dissipation for absorbed power.

Subsequent figures generally illustrate a top view of various configurations of integrated optical components. Example ~~semiconductor~~ L.B. Feb 7th 2002 M.P. Feb 7th 2002 materials used for fabricating such devi~~s~~ c es include InP, GaAs and $LiNbO_3$. L.B. Feb 7th 2002 M.P. Feb 7th 2002

An integrated optical circuit is illustrated in FIG. **2A** wherein a 1-to-1 imaging MMI device **202** is provided as mode stripper in series between a fiber **212** and a power splitting structure **204**, which may be, for instance, a multimode interference (MMI) device, a directional coupler, a star coupler, etc. The fiber **212** supplies an optical signal to an input waveguide **208** from which the optical signal is passed to the mode stripper **202**. The output of the power splitting structure **204** is split between a first output waveguide **210X** and a second output waveguide **210Y**. The optical signals on the first output waveguide **210X** and the second output waveguide **210Y** are carried to further integrated circuitry.

An alternate integrated optical circuit to that in FIG. **2A** is illustrated in FIG. **2B** wherein the mode stripper **202** is provided in series with and after a waveguide device **206**, which may be, for instance, a Semiconductor Optical Amplifier (SOA), a

Laser, etc. The output of the mode stripper **202** is carried on an output waveguide having an angled facet **211**.

As will be apparent to a person skilled in the art, the MMI region of the mode stripper **202** of FIGS. **2A** and **2B** may have the structure of any one of the examples in FIGS. **1B**, **1C** or **1D** or a combination thereof.

A first exemplary integrated optical circuit **300** is illustrated in FIG. **3**. The first exemplary integrated optical circuit **300** includes an SOA **304** and has an input waveguide **308** and an output waveguide **310**. The input waveguide **308** has a coated and angled facet **309** and the output waveguide **310** has a coated and angled facet **311**. An input mode stripper **302A** is arranged in the input optical path to the SOA **304** and an output mode stripper **302B** is arranged in the output optical path.

A second exemplary integrated optical circuit **400** is illustrated in FIG. **4**. The second exemplary integrated optical circuit **400** includes a waveguide device **406** in series with and interposed between the input waveguide **308** and the output waveguide **310** of FIG. **3**, in place of the SOA **304**.

An SOA **500** is illustrated in FIG. **5** which includes a multimode interference (MMI) region **512** connected to an input waveguide **508** and an output waveguide **510**. As is typical, the SOA **500** includes an electrode **504**. The input waveguide **508** has a coated and angled facet **509** and the output waveguide **510** has a coated and angled facet **511**. As will be apparent to a person skilled in the art, the MMI region **512** of the SOA **500** may have the structure of any one of the examples in FIGS. **1B**, **1C** or **1D** or a combination thereof.

A partial integrated optical circuit is illustrated in FIG. **6** to show an alternate configuration of a 1-to-1 imaging MMI device **600** as an alternate mode stripper. As may be seen to be typical given the configurations hereinbefore, the alternate mode stripper **600** includes an MMI region **612** connected to an input waveguide **608** and an output waveguide **610**. However, the alternate mode stripper **600** of FIG. **6** also includes two further waveguides on the output leading to a first dump port **614A** and a second dump port **614B**. Each of the dump ports **614A, 614B** includes a respective photodetector **620A, 620B**. As will be apparent to a person skilled in the

art, the MMI region **612** of the alternate mode stripper **600** may have the structure of any one of the examples in FIGS. **1B**, **1C** or **1D** or a combination thereof.

An exemplary optical integrated circuit **700** is illustrated in FIG. **7** including a 1-to-1 imaging MMI device **702** for use as a mode stripper and an interferometric modulator **720**. The exemplary optical integrated circuit **700** further includes an input waveguide **708** that supplies an input signal to the mode stripper **702**, an intermediate waveguide **718** leading from the mode stripper **702** to the interferometric modulator **720** and an output waveguide **710** for carrying an output signal from the interferometric modulator **720**. The interferometric modulator **720** includes an input optical power splitter **722** connected to an output optical power combiner **724** by an upper waveguide **728U** and a lower waveguide **728L**. The lower waveguide **728L** includes a phase altering device (PAD) **726**. The PAD may be, for instance, a device whose index of refraction is alterable through the application of a voltage. Notably, the interferometric modulator **720** may be considered as the waveguide device **206** of FIG. **2** or the waveguide device **406** of FIG. **4**. Furthermore, the input optical power splitter **722** and the output optical power combiner **724** have been illustrated as 2-to-2 devices. In other implementations of the interferometric modulator **720**, the input optical power splitter **722** may be a 1-to-2 device. Additionally, the output optical power combiner **724** may be a 2-to-1 device.

The dimensions of the MMI region **112**, **512**, **712** in each of the above embodiments are selected, relative to the frequency of the input, so that the output of the MMI device is primarily the fundamental mode of the input signal.

In overview with reference to FIG. **2A**, misalignments between fiber **212** and the input waveguide **208**, which can excite higher order waveguide modes that may beat to cause lateral waveguide field oscillations, may be compensated for by stripping these higher order modes from a signal input to the power splitting structure **204**. Thus, the mode stripper **202** (FIG. **2A**) can significantly reduce or remove variations in the power splitting ratio of the power splitting structure **204**. By choosing the dimensions of the mode stripper **202** appropriately, the image of the signal at the input that is available at the output may have only a fundamental mode. Fixing the power splitting ratio is critical to the performance of interferometric modulators. The

mode stripper **202** can therefore increase the manufacturing tolerances of modulator devices or improve the modulator performance. Advantageously, reducing these lateral waveguide field oscillations will prevent an increase in crosstalk where the power splitting structure **204** is an optical switch.

In view of FIG. **2B**, the mode stripper **202** is placed prior to the angled facet **211** of the waveguide device **206**. The mode stripper **202** may, in this configuration, greatly reduce the higher order optical backreflections (both guided and radiation) that would otherwise return from the angled facet **211** to the waveguide device **206**.

In particular, the dimensions of the mode stripper **202** may be selected so that the signal at the output is an image of the signal at the input and includes only the fundamental mode. Here, the terms “input” and “output” are used relative to the direction of the signal under consideration. For example, when considering backreflections in FIG. **2B**, the direction of the backreflections is right to left, so the right side of the mode stripper **202** may be considered the input and the left side may be considered the output. As backreflections consist mainly of higher order modes, very little evidence of any backreflections that enter the right side may be seen at the left side.

This configuration could generally improve the usefulness of waveguides with angled facets in many strongly guided waveguide device. Exemplary strongly guided waveguide structures include modulators, mode converters and arrayed waveguide gratings (AWGs). Use of the mode stripper **202** is also applicable to buried or weakly guided waveguides.

A popular way to amplify optical signals involves the use of an Erbium Doped Fiber Amplifier (EDFA) wherein a section of fiber is doped with Erbium such that, when that section is pumped with an external radiation (light) source, the optical signal passing through the section is amplified. In contrast, a Semiconductor Optical Amplifier (SOA) involves an “active” section of semiconductor waveguide in contact with an electrode. Rather than pumping with light, as in the EDFA case, the electrode is electrically pumped with electrical energy such that an optical signal passing through the active section is amplified.

In FIG. **3**, the input mode stripper **302A** is arranged in series with the SOA **304** and the output mode stripper **302B**. The input mode stripper **302A** acts to reduce lateral waveguide field oscillations that may result from misaligned optical coupling. Both the input stripper **302A** and the output mode stripper **302B** act to reduce the backreflections that would otherwise be received from the angled facets **309**, **311**. Backreflections are a significant contributor to the noise figure (discussed hereinafter) of an SOA and must be carefully controlled.

Similarly, in FIG. **4**, the input mode stripper **302A** is arranged in series with the waveguide device **406** and the output mode stripper **302B**. The input mode stripper **302A** acts to reduce lateral waveguide field oscillations that may result from misaligned optical coupling. Both the input mode stripper **302A** and the output mode stripper **302B** act to reduce the backreflections that would otherwise be received from the angled facets **309**, **311**.

As illustrated in FIG. **5**, the structure of a mode stripper and an SOA can be complementary. In the SOA **500** of FIG. **5**, the MMI region **512**, which might be considered part of a mode stripper, is the active section of the SOA **500**. The electrode **504** may be electrically pumped to operate the SOA **500**. The electrode **504** should be shaped to optimize the gain of the fundamental mode in the MMI region **512**. Previous literature **[inventor not certain of origin]** has proposed a diamond as the optimal shape for the electrode **504** in other SOA applications. This SOA/MMI structure provides poor overlap between higher order mode reflections from the waveguide facets and the gain region.

Often a measure of the performance of an optical component, such as an SOA device, is given as a "noise figure", which is the ratio of the output signal-to-noise ratio of the SOA device to the input signal-to-noise ratio, assuming the input signal-to-noise ratio is shot noise limited.

Backreflections, in general, effect SOA noise figures and also may effect the linewidth of tuned, gain-controlled lasers. Where a mode stripper is placed prior to each of the angled and coated facets of a given device to reduce backreflections, the higher order modes reflected from the facets may be scattered by the mode stripper,

thereby reducing feedback into the device. It has been found that reducing backreflections results in improved noise figures for SOAs in particular.

During the operation of the alternate mode stripper **600** of FIG. **6**, the alternate mode stripper **600** acts to couple an optical signal, received from the input waveguide **608**, to the output waveguide **610**. Under normal operating conditions, the fundamental mode of the optical signal received from the input waveguide **608** passes through the MMI region **612** unimpeded, while the higher order radiation and guided modes are directed out the two dump ports **614A**, **614B**. Just as the placement of the output waveguide **610**, is chosen to receive the fundamental mode of the input optical signal, the placement of the two dump ports **614A**, **614B** may be chosen for optimal coupling of higher order and radiation modes. The alternate mode stripper **600** may minimize backreflections, from facets beyond the output waveguide **610**, in manner similar to the operation of mode strippers described hereinbefore. However, the overall size of the alternate mode stripper **600** is larger than the earlier described mode strippers such that the additional output waveguides may be accommodated. By receiving a signal from the photodetector **620A** in the first dump port **614A** and the photodetector **620B** in the second dump port **614B**, it is possible to monitor for changes in the device coupling over time and provide a feedback mechanism without tapping the primary signal emanating from the output waveguide **610**.

The interferometric modulator **720** in the exemplary optical integrated circuit **700** illustrated in FIG. **7** typically operates as follows. The power in an input signal received on the intermediate waveguide **718** is split in a predetermined power splitting ratio by the input optical power splitter **722**. At the output optical power combiner **724**, signals received on each of the upper waveguide **728U** and the lower waveguide **728L** are combined to form an output on the output waveguide **710**. Through the use of the PAD **726**, the signals in the upper waveguide **728U** and the lower waveguide **728L** may arrive at the output optical power combiner **724** out of phase with each other. The power in the output signal on the output waveguide **710** is dependent upon the degree to which the signals are out of phase. By controlling the PAD **726** with a modulating signal, the output may be modulated with the modulating signal.

Predictable operation of the interferometric modulator **720** depends upon fixing the power splitting ratio in the input optical power splitter **722**. For this reason, the mode stripper **702** is introduced in advance of the interferometric modulator **720**. By stripping any higher order modes that can cause lateral waveguide field oscillations in an input signal after a misaligned coupling to the input waveguide **708**, the mode stripper **702** improves the performance of the interferometric modulator **720**.

FIG. **8** illustrates the impact of an embodiment of the present invention on ~~a~~ I.B. Feb 7th 2002 M.D. Feb 7th 2002 the split ratio of a Butterfly MMI. In particular, a mode stripper having dimensions of 6 μm by 80 μm is used. The split ratio is plotted, in a graph **800**, for the Butterfly MMI with and without the mode stripper over a number of values of misalignment. Clearly, the addition of the mode stripper significantly reduces the effect of misalignment on the split ratio.

Other modifications will be apparent to those skilled in the art and, therefore, the invention is defined in the claims.